EVALUATING WEPP-PREDICTED INFILTRATION, RUNOFF, AND SOIL EROSION FOR FURROW IRRIGATION

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ABSTRACT. *The Water Erosion Prediction Project (WEPP) model contains a furrow irrigation component to simulate hydrology and erosion in irrigation furrows. It currently is the only multiple-event furrow erosion simulation model available for public use. However, the furrow irrigation component has not been evaluated yet. Therefore, we evaluated the WEPP model for furrow irrigation by comparing predicted infiltration, runoff, and soil loss with field measurements from three southern Idaho studies on Portneuf silt loam (coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocalcids). Baseline effective hydraulic conductivity, rill erodibility, and critical shear were calibrated using data measured from the upper quarter of two fields. Calibrated effective hydraulic conductivity was within the range of WEPP-defined values for Portneuf soil. Calibrated rill erodibility of 0.0003 s m^{-1} was almost two orders of magnitude less than the WEPP-defined value of 0.02 s m^{-1}, while calibrated critical shear of 1.2 Pa was about one-third of the WEPP-defined value of 3.5 Pa. Predicted infiltration correlated poorly with measured infiltration for most fields. Regression coefficients for predicted versus measured infiltration ranged from –0.07 to 0.35, indicating that predicted infiltration did not vary with measured infiltration. Predicted soil loss correlated well (R^2 = 0.57) with measured soil loss from the upper end of the two fields used to calibrate erodibility parameters. At the field ends however, runoff was underpredicted and soil loss was overpredicted. When runoff was predicted reasonably well for an irrigation, cumulated predicted soil erosion across a field did not match cumulated measured erosion at field quarter segments because transport capacity was overpredicted. Deposition was not predicted unless runoff was greatly under-predicted. The WEPP model cannot be recommended for use with furrow irrigation until erodibility parameters and sediment transport are better defined for irrigation furrows.*
Keywords. *Furrow irrigation, Erosion modeling, WEPP.*

The goal of the Water Erosion Prediction Project (WEPP) was to develop new water erosion prediction technology for soil and water conservation planning and assessment (Nearing et al., 1989). The WEPP model includes an irrigation component for estimating soil loss from sprinkler- and furrow-irrigated fields. Erosion processes (i.e., soil detachment and transport) during irrigation and rainfall are similar. However, the systematics of furrow irrigation erosion differ from the simulated rainfall conditions that were used to define functional relationships and soil parameters for the WEPP model. For example, water initially flows onto dry soil during furrow irrigation, but rainfall wets soil before water begins to flow in rills. Furrow flow rate also decreases with distance and increases with time, which is not typically the case for flow in rills. Runoff during furrow irrigation also tends to last longer than during a rainfall runoff event.

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The hydrology component of the WEPP model is critical to erosion prediction because rill erosion is calculated as a function of hydraulic shear (Laflen et al., 1991). Infiltration is calculated in the WEPP furrow irrigation component using a two-dimensional approximation of the Green-Ampt infiltration equation as presented by Fok and Chiang (1984) and described in the WEPP technical documentation (Flanagan and Nearing, 1995). Runoff volume and peak runoff rate are calculated in a kinematic wave hydrology component. Effective runoff duration is then calculated by dividing runoff volume by peak runoff rate. These three parameters (runoff volume, duration and peak rate) are used in the steady-state erosion component to predict sediment detachment, transport and deposition.

The WEPP model categorizes soil erosion into rill and interrill processes. Interrill erosion involves soil detachment and transport by raindrops and shallow sheet flow. Rill erosion processes describe soil detachment, transport and deposition in rill channels (Flanagan and Nearing, 1995). Furrow erosion in the WEPP model is assumed to be identical to rill erosion under rainfall conditions. Detachment in rills occurs only when hydraulic shear exceeds the soil critical shear and sediment load is less than rill transport capacity. If sediment load exceeds transport capacity, sediment deposition occurs.

Soil detachment capacity by flowing water in rills is calculated by:

$$D_c = K_r (\tau - \tau_c)^a \tag{1}$$

where D_c is detachment rate for clear water (kg $s^{-1}m^{-2}$), K_r is rill erodibility [(s $m^{-1})^{-a}$], τ is hydraulic shear of flowing water (Pa), τ_c is soil critical shear (Pa), and a is a constant set equal to 1.0 in the WEPP model (Elliot and Laflen, 1993; Flanagan and Nearing, 1995). Hydraulic shear is calculated by:

$$\tau = \gamma RS \qquad (2)$$

where γ is the specific weight of water (N m^{-3}), R is the hydraulic radius of the rectangular rill (m), and S is the hydraulic gradient, which approximately equals the slope of the rill bottom.

Baseline rill erodibility and critical shear represent erodibility characteristics of freshly tilled soil. These two parameters were determined for several characteristic soils (including Portneuf) during WEPP rainfall simulations (Elliot et al., 1989). They can also be estimated from soil texture and organic matter content (Flanagan and Nearing, 1995). Rill erodibility and critical shear are adjusted daily in the model by multiplying the baseline values by adjustment factors. Adjustment factors account for residue incorporation; temporal changes in roots, sealing, and crusting; and freezing and thawing (Flanagan and Nearing, 1995).

The amount of soil detached in a rill is affected by the sediment concentration of the water flowing in the rill. Net soil detachment is calculated by:

$$D_f = D_c(1 - G/T_c) \qquad (3)$$

where D_f is net detachment rate (kg $s^{-1}m^{-2}$), G is sediment load in the rill (kg m^{-1} s^{-1}), and T_c is transport capacity of the rill (kg m^{-1} s^{-1}). Transport capacity is calculated by the following simplified transport equation:

$$T_c = k_t\tau^{3/2} \qquad (4)$$

where k_t is a transport coefficient ($m^{1/2}$ s^2 $kg^{-1/2}$). The transport coefficient is calculated from the transport capacity determined at the end of a uniform slope as described by Finkner et al. (1989).

The WEPP model is currently the only model available for public use that simulates erosion from multiple furrows for multiple years. However, furrow erosion predictions by the model have not been evaluated. Therefore, our objective was to evaluate the WEPP model under furrow irrigated conditions by comparing predicted infiltration, runoff and soil erosion with field measurements from three southern Idaho irrigation studies. One study involved three different furrow inflow rates and the other two studies involved several tillage treatments.

Materials and Methods

Field Measurements—Study 1

Data for study 1 were taken from Trout (1996). This study was conducted on two fields, both Portneuf silt loam (coarse-silty, mixed, superactive, mesic *Durinodic Xeric Haplocalcids*), at the Northwest Irrigation and Soils Research Laboratory near Kimberly, Idaho. Irrigation furrows were divided into four equal-length sections (one-fourth, one-half, three-fourths, and field end). Furrow flow rate was monitored at the end of each section using small, trapezoidal, long-throated flumes. Sediment concentration samples were collected from the flume discharge and poured into 1-L Imhoff cones. Sediment volume was read after settling for 30 min (Sojka et al., 1992). Flow rates and sediment concentrations were measured 15 min, 30 min, 1 h, 2 h, 4 h, 6 h, and 8 h after runoff started at each monitoring station and at the end of each 12 h irrigation.

Both fields were irrigated using water from the Twin Falls Canal Company (EC = 0.5 dS m^{-1}, SAR = 0.4 to 0.7). Three inflow rates were used during each irrigation. A medium inflow rate was chosen prior to each irrigation to give approximately 35% runoff and a 2-h advance time (typical for the area). High and low inflow rates were 20% above and below the medium inflow rates, respectively.

Field 1 was 204 m long with 1.3% slope (table 1). This field was moldboard plowed, roller harrowed and planted to dry beans (*Phaseolus vulgaris* L.). Five of the six irrigations on field 1 were monitored. Field 2 was 256 m long with 0.52% slope (table 1). This field was disked in the fall, roller harrowed in spring and planted to corn (*Zea mays* L.). Six of the nine irrigations on this field were monitored.

Field Measurements—Study 2

The second study was conducted from 1995 to 1997 at the Northwest Irrigation and Soils Research Laboratory near Kimberly, Idaho. It involved four tillage treatments: disk (D), paratill (P), disk and paratill (DP), and no-till (NT). The soil was Portneuf silt loam on a uniform 0.8% slope (table 1). Barley (*Hordeum vulgare*, L.) was grown the year prior to runoff and soil erosion measurements. Following barley harvest in 1995, stubble was cut about 80 mm high, baled and removed from the plots. The D and DP plots were disked after straw was removed in the fall of 1995 and in the spring of 1996 before planting dry beans. DP and P plots were paratilled approximately one month before planting. Paratill shanks were spaced 1.5 m apart. Each shank tilled the bed between two, 1.1-m spaced irrigation furrows. Thus, irrigation furrows were not disturbed by paratilling. Two dry bean rows were seeded 0.56 m apart between 1.1-m spaced irrigation furrows. Tillage operations in 1997 were similar to 1996 except the field was cultivated twice for weed control in 1997.

The field was irrigated six times in 1996 and five times in 1997 using water from the Twin Falls Canal Company. Irrigation duration varied from 8 to 24 h (table 2). Since inflow rates were not set identically for all furrows, average inflow rates among tillage treatments varied from 10 to 20%. Water flow and sediment loss were measured during five of six irrigations in 1996 and all five irrigations in

Table 1. Field conditions for studies 1, 2, and 3

Study	Year	Crop	Length (m)	Slope (m/m)	Row Spacing (m)	Furrow Spacing (m)	Tillage
1	1994	Dry bean	204	0.013	0.56	1.1	Spring moldboard plow, roller harrow
	1994	Corn	256	0.005	0.76	1.5*	Fall disk, spring roller harrow
2	1996	Dry bean	84	0.008	0.56	1.1	Spring disk, disk-paratill,
	1997	Dry bean	84	0.008	0.56	1.1	paratill or no-till
3	1989	Potato	67	0.007	0.92	1.8*	Fall disk, chisel or moldboard
	1990	Potato	107	0.009	0.92	1.8*	plow, spring paratill

* Irrigated alternate furrows during successive irrigation events.

Table 2. Irrigation dates and durations for study 2

1996 Irrigation	Date	Duration (h)	1997 Irrigation	Date	Duration (h)
1	7-9 May	12	1	1-2 July	8
2	1-2 July	24	2	10-11 July	24
3	11-12 July	12	3	23-24 July	24
4	24-25 July	12	4	4-5 Aug.	12
5	6-7 Aug.	24	5	25-26 Aug.	12
6	20-21 Aug.	10			

1997 with methods similar to those for study 1. Four furrows in each plot were monitored approximately 85 m from the irrigation supply ditch, about one-third the length of the field. Monitoring the upper third of the field resulted in high erosion rates because erosion tends to occur near the upper end and deposition near the lower end of a uniform slope (Brown and Kemper, 1987; Trout, 1996). Two of the four furrows were wheel-compacted when furrows were made. The other two furrows were wheel-compacted during planting and paratilling. As a result, infiltration was similar among all furrows.

Field Measurements — Study 3

Study 3 data were from Sojka et al. (1993). The effects of three fall tillage treatments (disk, chisel plow, and moldboard plow), with and without spring paratilling, on runoff and erosion from potato fields were tested. The study was conducted on two different fields, both Portneuf silt loam. Field 1 was 67 m long with 0.7% slope and field 2 was 107 m long with 0.9% slope. Fields 1 and 2 were irrigated 24 and 23 times, respectively, during the growing season. Each irrigation lasted 5 to 12 h, depending on crop water needs. Every other furrow was irrigated during an irrigation, making the furrow spacing 1.8 m. Alternate furrows were irrigated during the next irrigation. Each monitored furrow received the same inflow rate. Water flow and sediment loss at the end of the field were measured during each irrigation with similar methods as used in study 1.

WEPP Model Simulations

Version 98.4 of the WEPP model was run in continuous simulation mode. Actual weather data from an automated weather station near Kimberly, Idaho, were used for the climate input files. One overland flow element (OFE) was used to represent the uniform slopes and soils in each field. Management files were created to match field conditions as closely as possible. Maximum canopy height, in-row plant spacing and maximum rooting depth were changed to better represent crops grown during these three studies. The biomass energy ratio, which represents the potential crop growth per unit of intercepted photosynthetically active radiation (Flanagan and Livingston, 1995), and harvest index for each crop were adjusted so representative crop yields were achieved for preliminary simulation runs. WEPP-model tillage implement scenarios were edited to match disking, paratilling, planting and bean cutting field operations. Two field operations were not adequately described by model scenarios and had to be defined. First, a new scenario was created for a corrugator, the furrow-forming tool. Second, the rotary hoe scenario was changed to 10% surface disturbance to resemble limited surface disturbance caused by hand weeding with a hoe.

A one-year simulation run was made for each field and furrow inflow rate for study 1. A two-year run was made for each tillage treatment and replication for study 2. Separate irrigation files were created using average inflow rates for each replication of a treatment because equal inflow rates were not used for each furrow. For study 3, a two-year run was made for each field and tillage treatment, although runoff and erosion were monitored only during the second year. Two-year simulations were used for study 3 because accurate tillage and irrigation information were available for the previous year. One irrigation file was used for each field of study 3 because inflow rate was equal for all furrows.

Crop row spacing had to be changed to 1.1 m for dry bean, 1.5 m for corn, and 1.8 m for potato because furrow spacing is set equal to row spacing in the WEPP model. These row spacings are double the actual spacings because two bean rows were planted between irrigation furrows and alternate corn and potato furrows were irrigated. In-row crop spacings in the model were half the actual spacing so plant populations were equal between the model and field. Permanent rills were used so that the model did not form new rills during the first irrigation after each tillage. Rill width was fixed at 0.10 m and was not calculated by the model.

Predicted runoff, infiltration and soil loss were graphically compared with measured values. Slope, intercept, and coefficient of determination were calculated by linear regression of measured and predicted values. Predicted and measured values were also compared using model efficiency (Nash and Sutcliffe, 1970). Model efficiency was calculated by:

$$\mathrm{ME} = 1 - \Sigma(\mathrm{m} - \mathrm{p})^2/\Sigma(\mathrm{m} - \mathrm{m_{ave}})^2 \quad (5)$$

where ME is the model efficiency coefficient, m is the measured value, p is the predicted value, and m_{ave} is the average of measured values. Model efficiency compares predicted values to the 1:1 line of measured equals predicted rather than comparing predicted values to the best regression line as is done with coefficient of determination. Model efficiencies near 1 indicate good agreement between measured and predicted values. Biased model results are indicated when model efficiency is less than the coefficient of determination. A negative model efficiency indicates that the average measured value is a better estimate than the model output.

Parameter Calibration

The WEPP model adjusted effective hydraulic conductivity. Baseline effective hydraulic conductivity was calibrated to fit the upper quarter field data from both study 1 fields. Baseline conductivity values from 2.6 to 3.4 mm h^{-1} were tested to determine the optimum value, which was chosen by minimizing the sum of the square of the difference between predicted and measured runoff.

Calculated hydraulic shear in measured irrigation furrows was less than 2.5 Pa (Trout, 1992). Therefore, no soil detachment would be predicted using the WEPP default baseline critical shear of 3.5 Pa for Portneuf soil. Consequently, baseline rill erodibility (K_r) and critical shear stress (τ_c) values were calibrated with a similar method as effective hydraulic conductivity. Optimum baseline values were chosen by minimizing the sum of the square of the difference between predicted and measured soil loss from the upper quarter of both fields in study 1, using the calibrated baseline effective hydraulic conductivity. Since soil detachment is the dominant mechanism on the upper quarter of a furrow-irrigated field (Trout, 1996), the calibration runs tested the WEPP model detachment algorithms without deposition. Shorter furrow lengths would be preferred to ensure that soil deposition did not occur, but we were limited by available data. Baseline critical shear values from 0.7 to 2.0 Pa and baseline rill erodibility values from 0.0001 to 0.0006 s m^{-1} were chosen by trial and error for the calibration runs.

Yield Sensitivity

Yield prediction errors can result in crop residue and water-use prediction errors, both of which affect soil erosion predictions. Two sets of simulations were run to determine the effect of predicted crop yield on predicted runoff and soil loss. The biomass energy ratio was increased and decreased by 50 to 60% for study 1 crops. The biomass energy ratio was increased from 25 to 40 kg MJ^{-1} for dry beans and from 40 to 60 kg MJ^{-1} for corn. The ratio was also decreased to 12 kg MJ^{-1} for dry beans and 20 kg MJ^{-1} for corn. We then compared runoff and soil loss predicted with increased, decreased and optimum biomass energy ratios as an indication of model sensitivity to crop yield.

Results

Overall the WEPP model was flexible enough to represent most field input conditions. One major limitation was that the model automatically set furrow spacing equal to row spacing. It is common practice in many areas to irrigate every other furrow or to plant two crop rows between irrigation furrows. If model row spacings were set equal to field row spacings, the simulated inflow volume would have been twice as much as the actual inflow because the model furrow spacing would be half the field furrow spacing. Although model crop row spacing was twice the field row spacing, predicted crop yields were similar to average yields in southern Idaho because in-row crop spacings were decreased by one-half in the model so plant populations were the same as field conditions.

Another general problem is the model does not simulate furrow irrigation on days with 1 mm or more of rain. Therefore, irrigation dates in the model had to be changed by one or two days to avoid rains in the model climate file.

The WEPP model predicted evapotranspiration reasonably well. Predicted evapotranspiration fell within a range of values calculated from local weather station data for dry beans, corn, and potatoes. Soil water content was adequately predicted compared to measured soil water content for study 2 based on a cursory comparison. Soil water content data were not available for either study 1 or 3.

Parameter Calibration

The calibrated baseline effective hydraulic conductivity was 3.0 mm h^{-1}. This was slightly less than the WEPP default value of 3.4 mm h^{-1} for Portneuf soil, but equaled the estimated baseline effective hydraulic conductivity shown in the WEPP Users Summary (Flanagan and Livingston, 1995). Although predicted infiltration was generally within 20% of measured infiltration, correlation between measured and predicted infiltration for the calibration data set was poor (fig. 1). The slope of the best-fit line was near zero (0.08), meaning predicted infiltration did not increase or decrease with measured infiltration. Coefficients of determination were 0.04 for the bean field (field 1) and 0.75 for the corn field (field 2). The large coefficient of determination for the corn field resulted from under-predicting infiltration by 35 to 40% for irrigation 1 (three data points on the far right in fig. 1). If irrigation 1 for the corn field were removed from the analysis, coefficients of determination were 0.18 for field 2 and 0.0004 for both fields combined. Model efficiency coefficients were –0.45 for the bean field, 0.04 for the corn field including irrigation 1, and –0.07 for the corn field without irrigation 1. The negative coefficients indicate that averages of measured values represent the measured data better than model-predicted values.

Predicted and measured runoff correlated very well for the upper quarter data from study 1 (fig. 1), but this is to be expected because only 20 to 25% of the inflow infiltrated on the upper quarter of the field. Therefore, most of the variation in runoff was caused by variations in inflow, which is an input value. Consequently, a 50% error in predicted infiltration results in less than 5% error in runoff for the upper quarter. As a greater percentage of the inflow infiltrates, poor infiltration predictions by the model will cause greater runoff prediction errors.

The best correlation between measured and predicted soil loss values for the upper quarters of the study 1 fields

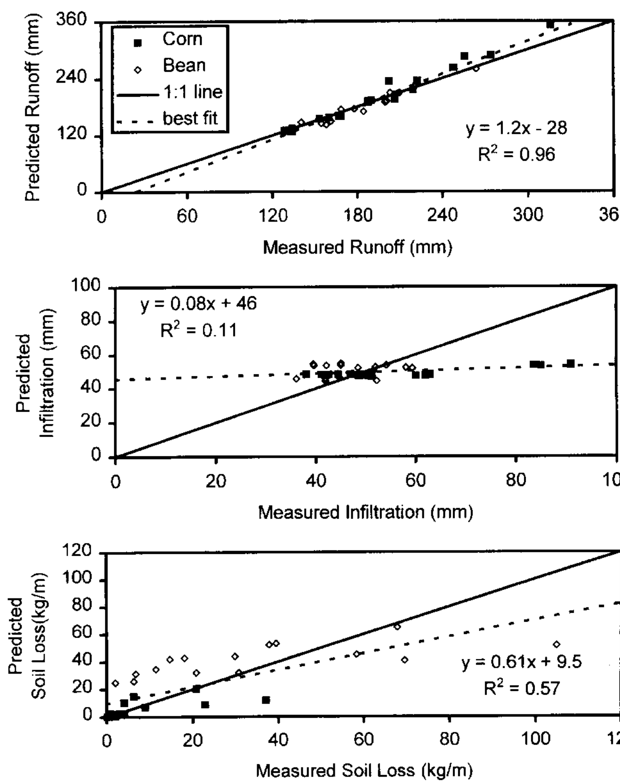

Figure 1–WEPP-predicted versus measured runoff, infiltration, and soil loss for the upper quarter of the study 1 corn and bean fields used for WEPP-parameter calibration.

occurred with K_r = 0.0003 s m^{-1} and τ_c = 1.2 Pa. Coefficients of determination were 0.48 for bean, 0.49 for corn, and 0.57 for bean and corn combined (fig. 1). Model efficiency coefficients were 0.33 for bean, 0.44 for corn, and 0.56 for bean and corn combined. The generally good agreement between model efficiency coefficients and coefficients of determination indicate the predicted soil loss for the upper ends of these fields was not biased by some systematic error. The calibrated baseline critical shear of 1.2 Pa was about one-third the model default value of 3.5 Pa, while the calibrated rill erodibility of 0.0003 s m^{-1} was almost two orders of magnitude less than the model default value of 0.02 s m^{-1}. These calibrated baseline values were used for simulation runs on all three studies since all fields had the same soil type.

Study 1

WEPP model predictions for the entire corn and bean fields were similar or poorer than for the upper quarter of the fields. The most concerning aspect was the poor relationship between measured and predicted infiltration (table 3). Predicted infiltration was nearly constant, as indicated by regression coefficients of –0.07 for bean and 0.25 for corn. The model overpredicted infiltration for all irrigations and inflow rates except irrigation 1 on the corn field (fig. 2). Overpredicting individual irrigations resulted in over prediction of annual infiltration by 45 to 55% for the bean field. Total infiltration for the corn field was overpredicted by only about 10% because irrigation 1 was underpredicted by approximately 20% while all other irrigations were overpredicted by 10 to 40%. The WEPP-adjusted effective hydraulic conductivity of 2.88 mm h^{-1} was too low for the first corn irrigation, indicating improper model characterization of soil or tillage effects on effective hydraulic conductivity. The effective hydraulic conductivities for the remaining irrigations on the corn field ranged from 2.72 (last irrigation) to 2.98 mm h^{-1} (second irrigation). The coefficient of determination between measured and predicted infiltration on the corn field decreased from 0.82 to 0.25 when irrigation 1 was eliminated from the analysis.

Table 3. Annual measured and predicted runoff, infiltration, and sediment yield for study 1 (slope, intercept, R^2, and ME* were calculated from individual irrigation events)

	Runoff		Infiltration		Soil Loss	
Inflow Rate	Measured (mm)	Predicted (mm)	Measured (mm)	Predicted (mm)	Measured (kg m^{-1})	Predicted (kg m^{-1})
Field 1, Bean						
Low	78	7	160	232	69	48
Med	115	29	164	249	167	206
High	166	71	166	260	284	490
Slope	0.67		–0.07		1.12	
Intercept	–8.9		52		11	
R^2	0.86		0.005		0.44	
ME	–2.0		–32		–0.88	
Field 2, Corn						
Low	61	44	255	273	7	72
Med	107	88	265	283	16	116
High	184	160	267	291	70	180
Slope	0.94		0.25		0.81	
Intercept	–2.1		36		16	
R^2	0.55		0.82		0.17	
ME	0.17		0.34		–5.0	

* Model efficiency coefficient calculated from equation 5 as described by Nash and Sutcliffe (1970).

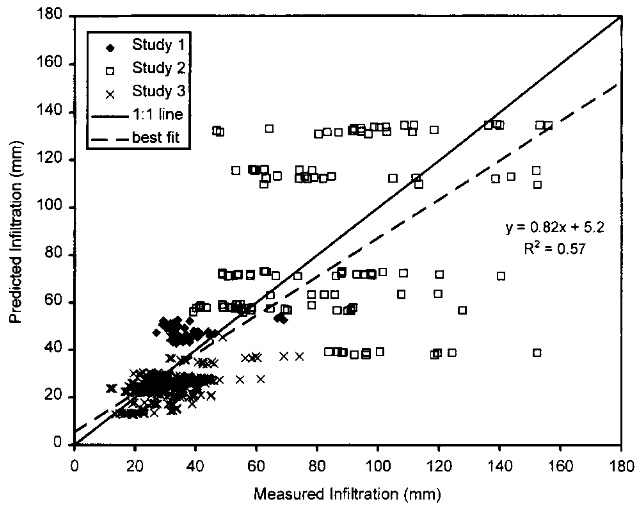

Figure 2–WEPP-predicted versus measured infiltration for irrigations from studies 1, 2, and 3.

As expected, predicted and measured runoff correlated better than infiltration (table 3). A portion of the predicted runoff response was due to inflow, an input value, because the WEPP-model irrigation component first calculates infiltration and then calculates runoff by subtracting infiltration from inflow. Since infiltration was overpredicted for all events except the first corn irrigation, runoff was underpredicted for all events except the first corn irrigation (fig. 3). Accurately predicting runoff is critical since the steady state runoff rate is used to calculate shear, which is the main variable in detachment and transport calculations.

Predicted and measured soil loss from the entire field correlated poorly for the corn field (R^2 = 0.17) and reasonably well for the dry bean field (R^2 = 0.44) (table 3).

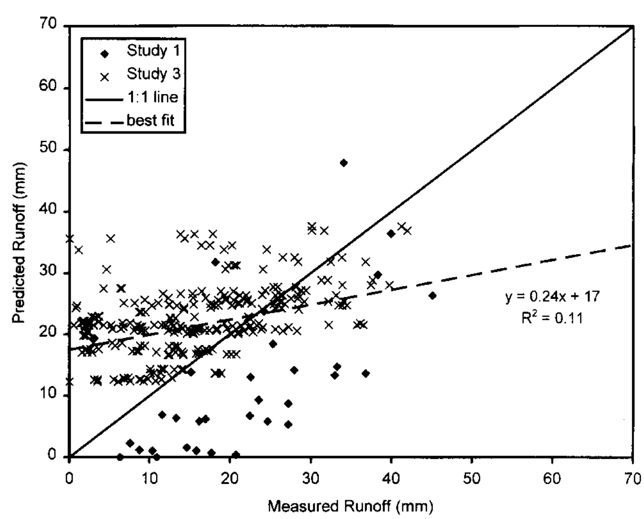

Figure 3–WEPP-predicted versus measured runoff for irrigations from studies 1 and 3. Study 2 was not included because runoff from the upper third of the field (100 to 500 mm) was much greater than end of field runoff from studies 1 and 3.

Based on negative model efficiency coefficients, predicted soil loss poorly represented measured data. Some soil loss prediction error resulted from runoff prediction error, especially for irrigation 1 on the corn field. However, the model underpredicted runoff while overpredicting soil loss for study 1 (figs. 3 and 4). WEPP model detachment algorithms were presumably correct since the model predicted soil loss from the upper quarter of both fields reasonably well (fig. 1). This indicates that transport capacity was overpredicted, causing excess sediment transport and insufficient deposition to be predicted down the furrow. The WEPP model only predicted deposition for the bean field. Field measurements, however, showed that essentially all soil detachment occurred on the upper quarter of both fields while sediment transport and deposition were dominant processes on the lower ends of the fields (Trout, 1996).

Cumulative soil erosion across the fields clearly shows that the WEPP model overpredicted transport capacity. For two representative bean irrigations, WEPP accurately predicted total soil loss at the end of the field when

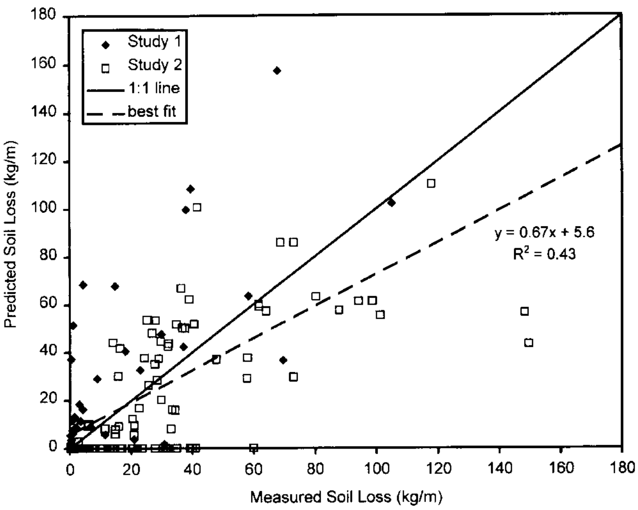

Figure 4–WEPP-predicted versus measured soil loss for irrigations from studies 1 and 2. The WEPP model did not predict any soil loss for study 3.

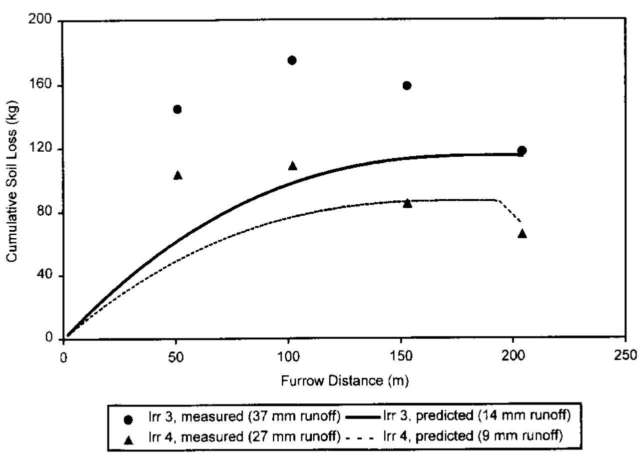

Figure 5–Measured and predicted on-field erosion distribution for irrigations 3 and 4 on the study 1 bean field. Runoff was greatly underpredicted for these two irrigations.

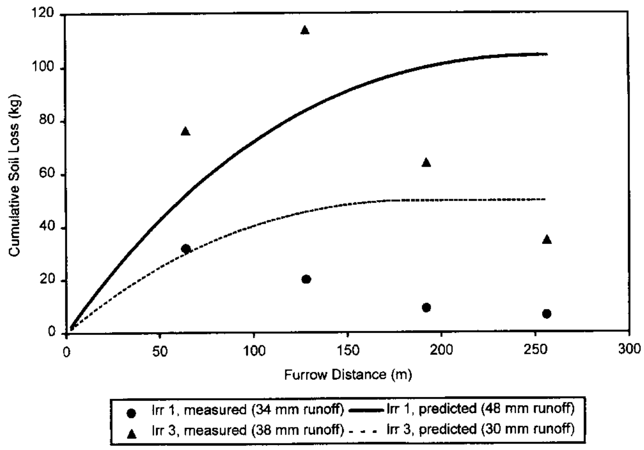

Figure 6–Measured and predicted on-field erosion distribution for irrigations 1 and 3 on the study 1 corn field.

predicted runoff was 30 to 40% of the measured amount (fig. 5). When runoff was more accurately predicted, deposition was not predicted and total soil loss was overpredicted (fig. 6). Altering baseline erodibility parameters will not affect predicted soil loss at the field end once predicted transport capacity is reached because soil is no longer being detached. Decreasing rill erodibility or increasing critical shear only reduces the detachment rate or the furrow distance over which detachment occurs.

Study 2

Runoff volume was much greater from study 2 than from study 1 because we monitored the upper third of the field and several irrigations lasted 24 h compared to 12 h for all irrigations in study 1. Similar to study 1, predicted and measured infiltration correlated poorly while predicted and measured runoff correlated reasonably well (table 4). Again, only about 30% of the inflow infiltrated on the upper end of the field that was monitored, which means most of the predicted and measured runoff variability results from inflow variations.

Predicted and measured soil loss correlated reasonably well for study 2 (table 4). However, no soil detachment was predicted for no-till and paratill tillage treatments for any irrigation the first year and for the first two irrigations the second year. The critical shear adjustment factor equaled 2.0 for no-till and paratill until dry beans were cut with a rod weeder on day 245, making the critical shear 2.6 Pa during the entire year 1 irrigation season, despite setting the rill tillage intensity to 0.9 for the corrugator (1.0 is maximum). No-till and paratill treatments were cultivated twice for weed control in year 2, causing the model to reduce the critical shear adjustment factor to less than 1.98 after the second cultivation. These results indicate that tillage parameters were improperly defined or the model inappropriately adjusted erodibility parameters for furrow irrigated conditions.

Annual runoff and infiltration were predicted reasonably well because prediction errors for individual events tended to offset each other. Annual runoff and infiltration prediction errors were less than 15%, while errors for individual events were up to 100%. Annual soil loss was overpredicted by 20 to 100% with the exception of disk-

Table 4. Annual measured and predicted runoff, infiltration and sediment yield for study 2 (slope, intercept, R^2, and ME* were calculated from individual irrigation events)

Tillage	Runoff Measured (mm)	Runoff Predicted (mm)	Infiltration Measured (mm)	Infiltration Predicted (mm)	Soil Loss Measured (kg m^{-1})	Soil Loss Predicted (kg m^{-1})
			Year 1			
Disk	960	982	439	452	65	49
Disk-paratill	931	926	383	451	47	37
No-till	964	980	445	459	18	0
Paratill	933	949	407	458	27	0
			Year 2			
Disk	1201	1250	372	398	253	190
Disk-paratill	1181	1305	484	389	180	217
No-till	1187	1210	406	398	261	123
Paratill	1004	1075	407	397	147	103
Slope	0.86		0.30		0.63	
Intercept	37		59		2.3	
R^2	0.68		0.07		0.52	
ME	0.62		–0.54		0.45	

* Model efficiency coefficient calculated from equation 5 as described by Nash and Sutcliffe (1970).

Table 5. Annual measured and predicted runoff and infiltration for study 3 (slope, intercept, R^2, and ME* were calculated individual irrigation events)

Tillage	Runoff Measured (mm)	Runoff Predicted (mm)	Infiltration Measured (mm)	Infiltration Predicted (mm)
		Field 1		
Chisel	578	584	628	602
Chisel-paratill	424	598	782	588
Disk	497	584	709	602
Disk-paratill	521	598	685	588
Moldboard	339	584	867	602
Moldboard-paratill	425	598	781	588
Slope	0.29		0.35	
Intercept	19		14	
R^2	0.20		0.28	
ME	–0.13		–0.06	
		Field 2		
Chisel	306	441	641	555
Chisel-paratill	214	452	732	543
Disk	312	441	634	555
Disk-paratill	224	452	722	543
Moldboard	285	441	662	555
Moldboard-paratill	200	452	746	543
Slope	0.06		0.18	
Intercept	20		19	
R^2	0.02		0.08	
ME	–1.4		–0.70	

* Model efficiency coefficient calculated from equation 5 as described by Nash and Sutcliffe (1970).

paratill treatment in year 2 which was underpredicted by 20%.

Study 3

Both predicted runoff and infiltration correlated poorly with measured data in study 3, especially for field 2 (figs. 2 and 3). Model efficiency coefficients were negative for runoff and infiltration for both years (table 5). Infiltration was underpredicted for almost every irrigation on both fields during both years, resulting in runoff being overpredicted. Runoff was monitored at the end of these fields, so 60 to 70% of the inflow infiltrated. The poor runoff and infiltration predictions may be partially due to the inability of the WEPP model to simulate alternate furrow irrigation. The model simulated all irrigations occurring on the same furrows at 1.8 m spacings. After each irrigation, the model uniformly distributed water in the soil between furrows. In reality, furrow spacing was 0.9 m and each furrow was irrigated every other time. Soil water content of recently irrigated furrows was probably greater than the alternate furrows which were irrigated three to five days earlier. In other words, the soil surface in furrows just before irrigation was probably drier than the adjacent furrows that were irrigated three to five days earlier. However, the model predicts a uniform soil water content which may be greater than the soil water content of the actual irrigation furrow. Simulating half as many irrigations on 0.9 m row spacing resulted in worse correlations between measured and predicted runoff.

Predicted runoff and infiltration did not vary among chisel plow, disk and moldboard plow treatments because effective hydraulic conductivity was equal among these fall tillage treatments after the soil thawed in the spring. Predicted runoff and infiltration only varied slightly between spring paratilled and non-paratilled treatments (table 5). Predicting equal infiltration for all fall tillage treatments is not a major concern because measured infiltration was significantly different among fall tillage treatments only during year 1. Paratilling only significantly affected measured infiltration and erosion during year 2 (Sojka et al., 1993).

The model did not predict any soil detachment for any irrigation of this study, even though runoff was overpredicted for most irrigations. However, measurable erosion occurred for the first six irrigations in year 1 and the first 17 irrigations in year 2. Annual total measured soil loss varied from approximately 6 to 120 kg m^{-1} (Sojka et al., 1993). The same baseline erosion values were used for this study as in studies 1 and 2. The model adjusted critical shear to 2.6 Pa by the third irrigation in year 1 and by the second irrigation in year 2, which was apparently too high for the field soil conditions. The model also did not predict any soil detachment when half as many irrigations were simulated with 0.9-m row spacing.

Yield Sensitivity

Only study 1 was used to compare predicted yield effects on predicted runoff and erosion because study 2 was monitored at the upper third of the field and study 3 had no erosion predicted. Increasing biomass energy ratios by approximately 50% more than doubled predicted bean yield and increased predicted corn yield about 60% compared to optimum biomass energy ratios that were used for all other simulations for study 1. Although predicted crop yield greatly increased, predicted runoff decreased less than 2% and predicted soil loss decreased 1 to 10%. Decreasing biomass energy ratios approximately 50% decreased predicted bean and corn yields about 90% and 60%, respectively. The lower biomass energy ratios increased predicted runoff only 1 to 2% and increased

Table 6. Annual predicted crop yield, runoff, and soil loss for study 1 showing effect of increased and decreased biomass energy ratios

	Field 1, Bean			Field 2, Corn		
	Biomass Energy Ratio					
Inflow Rate	12	25*	40	20	40*	60
	Crop Yield (Mg ha^{-1})					
Low	0.29	3.6	8.6	5.4	1.4	2.2
Med	0.31	3.8	8.9	5.4	1.4	2.2
High	0.32	3.9	9.0	5.4	1.4	2.2
	Runoff (mm)					
Low	7	7	7	45	44	43
Med	29	29	28	89	88	87
High	72	71	70	162	160	159
	Soil Loss (kg m^{-1})					
Low	48	48	48	76	72	66
Med	209	206	201	130	116	104
High	499	490	472	204	180	158

* Optimum biomass energy ratio used for all other simulation runs.

predicted soil loss 1 to 10% (table 6). These results indicate that WEPP-calculated furrow irrigation runoff and soil loss were not sensitive to crop yield. However, it is important to note that these were only one-year simulations. Altering the biomass energy ratio for multi-year simulations would probably have greater impact on predicted runoff and soil loss as biomass accumulates over several years.

Discussion

WEPP-model predictions were better when runoff and erosion rates were large (i.e., at the upper end of fields). This may partially result from the conditions under which the WEPP model was developed. WEPP field data collection involved simulated rainfall on 9-m long rills with 3 to 6% slope (5 to 6% slopes were used for Portneuf soil). Inflow was added at the top of each rill at 7 to 35 L min^{-1}. (Inflow rates for study 1 varied from 14 to 55 L min^{-1} for 204 and 256-m long fields). As a result of short rill length and high flow rates, erosion rates would be greater than typical rates occurring at the end of furrow irrigated fields. Also, runoff rates reach steady-state much faster than under our typical furrow irrigated conditions: a few minutes compared to approximately 2 h after runoff starts. These conditions could result in scaling problems when WEPP-defined relationships are applied to furrows longer than 100 m and irrigation durations longer than 12 h.

Another possible reason for poorer predictions for the ends of the fields is that erodibility and infiltration parameters might change with distance and time during an irrigation as detachment and deposition occur and surface seals form. Critical shear, rill erodibility, and effective hydraulic conductivity do not change in the WEPP model during an irrigation because it is a steady-state erosion model. These parameters also do not change with distance down a furrow in the model. However, Van Klaveren and McCool (1998) found that rill erodibility changed rapidly during 90-min flow tests with previously frozen soil in a tilting flume.

Since the WEPP model is a steady-state erosion model, runoff rate is constant during an event. The model uses the peak runoff rate as the constant runoff rate and then calculates an effective duration by dividing runoff volume by peak runoff rate, making a rectangular hydrograph with effective duration less than the actual duration. For the first few hours of irrigation, the peak runoff rate used by the model is greater than the actual runoff rate. During this time, sediment concentration also tends to be greatest (Trout, 1996). It is possible that a surface seal forming during the initial stage of irrigation protects, or armors, the soil from detachment. Consequently as furrow flow rate increases, less detachment occurs than would be predicted by a steady-state model. This may also be a reason why the calibrated rill erodibility was considerably less than the WEPP default value.

Detachment capacity in the WEPP model is a linear function of hydraulic shear stress (eq. 1). Calibrated baseline critical shear and rill erodibility used in this study were much less than WEPP-defined values. The line defined by the WEPP model baseline values had a slope (K_r) about 100 times greater and an x-intercept (τ_c) about three times greater than the line defined by calibrated baseline values. Since shear values calculated from WEPP rainfall simulation on Portneuf soil always exceeded 2.5 Pa, we do not know if the relationship between hydraulic shear and detachment capacity is non-linear ($a>1$ in eq. 1) or if furrow irrigation and simulated rainfall have two separate relationships. At low slopes (0.5 to 2%) and shear stresses (0.5 to 2 Pa) in a laboratory flume, Nearing et al. (1991) concluded that detachment rate was not a function of shear stress. They also found no appearance of a critical shear. At greater slopes (2 to 20%) and shear stresses (0.5 to 5 Pa), shear stress was linearly related to detachment rate with a critical shear of approximately 1 Pa (Shainberg et al., 1994), which was about one-third the WEPP value for that soil (3.3 Pa). These conflicting results indicate that additional research or better measurement tools are needed to identify appropriate shear-detachment relationships for irrigation furrows.

Conclusions

The WEPP model could not be used for furrow irrigation without modifications. Since the model uses a furrow spacing equal to row spacing, row spacing in the model must be doubled if two rows are planted between irrigation furrows or if alternate furrows are irrigated. Also, the model did not predict any soil detachment using the default baseline critical shear and rill erodibility values for this soil. Baseline critical shear and rill erodibility were calibrated using field data. WEPP model baseline values for Portneuf soil were three times greater for critical shear and almost 100 times greater for rill erodibility than calibrated baseline values. Since we evaluated the model with field data from only one soil type, we cannot recommend a procedure for adjusting critical shear and rill erodibility for other soils or areas. The model should not be used for predicting furrow irrigation erosion until critical shear and rill erodibility are defined for irrigation furrows.

Predicted infiltration correlated poorly with measured infiltration. Slopes of linear regression lines between measured and predicted infiltration were near zero, indicating that predicted infiltration did not correspond to measured infiltration. The model predicted runoff and erosion better from the upper end of fields where furrow flow rates were relatively insensitive to infiltration and furrow flow rates were more consistent during an irrigation. Soil loss predictions were inadequate for the end of furrow irrigated fields. The model overpredicted soil loss when runoff was accurately predicted for one field and accurately predicted soil loss when runoff was underpredicted for another field. Deposition was only predicted when runoff was greatly underpredicted or detachment was greatly overpredicted. These factors indicate that the WEPP model overpredicts transport capacity in irrigation furrows.

To accurately represent furrow irrigation, the WEPP model needs to account for alternate furrow irrigation and planting more than one row between irrigation furrows. The model also needs to simulate furrow irrigation when rainfall occurs. The furrow irrigation infiltration component should also be reconsidered based on the poor correlation between measured and predicted infiltration.

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